

Large t diffractive J/ψ photoproduction with proton dissociation in ultraperipheral pA collisions at LHC.

L. Frankfurt

*School of Physics and Astronomy,
Tel Aviv University, Tel Aviv, 69978 , Israel*

M. Strikman

*Department of Physics, Pennsylvania State University,
University Park, PA 16802, USA*

M. Zhalov

St. Petersburg Nuclear Physics Institute, Gatchina, 188300 Russia

Abstract

We evaluate the large momentum transfer J/ψ photoproduction with rapidity gaps in ultraperipheral proton-ion collisions at the LHC which provides an effective method of probing dynamics of large t elastic hard QCD Pomeron interactions. It is shown that the experimental studies of this process would allow to investigate the energy dependence of cross section of elastic scattering of a small $c\bar{c}$ dipole off the gluon over a wide range of invariant energies $10^3 < s_{c\bar{c}-gluon} < 10^6 \text{ GeV}^2$. The accessible energy range exceeds the one reached in γp at HERA by a factor of 10 and allows the kinematic cuts which improve greatly sensitivity to the Pomeron dynamics as compared to the HERA measurements. The cross section is expected to change by a factor ≥ 20 throughout this interval and our estimates predict quite reasonable counting rates for this process with the several of the LHC detectors.

1 Introduction

For many years investigations of the small x dynamics were focused on studies of the $\gamma^*(\gamma)p$ interactions at HERA. In particular, over the last decade significant efforts were aimed on the theoretical and experimental investigations of the high energy diffractive photo/electro production of vector mesons off proton target (for the recent review and references see [1]) including the hard processes in which a vector meson is produced with a large rapidity gap, Δy , between the vector meson V and the produced hadronic system X :

$$\gamma^* + p \rightarrow V + \text{gap} + X. \quad (1)$$

An important feature of these processes which occur due to the elastic scattering of small color singlet quark-antiquark ($q\bar{q}$) dipole configurations in the photon wave function (referred to as dipoles in the remainder of this article) off a parton within the proton target is the nontrivial interplay between evolution in $\ln(x_0/x)$ and $\ln(Q^2/Q_0^2)$. Study of high energy vector meson photoproduction in kinematics where momentum transferred through the gluon ladder exchange between dipole and a parton is large and the produced vector meson is separated by large rapidity gap from the products of target dissociation should allow to investigate $\ln(x_0/x)$ evolution at fixed momentum transfer t [2, 3, 4]. The HERA measured the relevant cross sections of ρ and J/ψ photoproduction [5, 6, 7, 8, 9] in a rather restricted γp center-of-mass range $20 \leq W_{\gamma p} \leq 200$ GeV and very limited range of Δy , making it very difficult to study the energy dependence of the amplitude predicted by the BFKL dynamics. Hence, it would clearly be beneficial to perform such measurements at higher $W_{\gamma p}$ and over a much larger range of Δy .

Here we extend our feasibility studies of [10], [11] for probing these processes in the proton-nucleus ultraperipheral collisions (UPCs)[12] at the LHC. The CMS and ATLAS detectors are well suited for such investigations since they cover large rapidity intervals. The ALICE detector maybe capable of studying this process in a certain rapidity range as well.

We consider J/ψ photoproduction by photon from the ultrarelativistic ion on the proton target in ultraperipheral pA collisions,

$$A + p \rightarrow A + \gamma + p \rightarrow A + J/\psi + X. \quad (2)$$

in the kinematics with large t and the rapidity gap Δy between J/ψ and the produced hadronic system X which is sufficiently large to suppress the fragmentation contribution.

The paper is organized as follows. In section 2 we discuss the QCD motivated formulas and parametrizations which could be used to describe the energy and t dependence of the considered process. Section 3 is devoted to analysis of the available HERA data on J/ψ production using parametrization of the data which is based on the hard mechanism of the reaction. In section 4 we estimate the rates of $\gamma + p \rightarrow J/\psi + \text{gap} + X$ reaction in pA collisions at LHC.

2 Energy and t dependence in the large t and rapidity gap quarkonium photoproduction

The main variables in such processes are the mass of the system produced in the proton dissociation, M_X , the square of momentum transfer $-t \equiv Q^2 = -(p_\gamma - p_V)^2$, and the square of the $q\bar{q}$ -parton elastic scattering energy

$$s_{(q\bar{q})j} = xW_{\gamma p}^2 = xs_{\gamma p} . \quad (3)$$

Here j denotes gluon or quark in the target and

$$x = \frac{-t}{(-t + M_X^2 - m_N^2)} , \quad (4)$$

is the fraction of the proton momentum carried by the target parton for a given M_X and t . At large t and $W_{\gamma p}$, the gap between the rapidity of the produced vector meson and the final-state parton at the leading edge of the rapidity range of the hadronic system X is

$$\Delta y = \ln \frac{xW_{\gamma p}^2}{\sqrt{(-t)(M_{J/\psi}^2 - t)}} . \quad (5)$$

It is rather difficult to measure M_X or x directly. However, they can be adequately determined by studying the leading hadrons close to the rapidity gap; full reconstruction is not required.

In kinematical region of large $-t \gg 1/r_{J/\psi}^2$ and $W_{\gamma p}^2 \gg M_X^2$ the quarkonium photoproduction cross section with target proton dissociation can be described as an incoherent sum of terms which are proportional to the product of the large t cross section of quarkonium photoproduction off the parton and the density of the parton j in the target [2, 3]:

$$\frac{d\sigma_{\gamma p \rightarrow J/\psi X}}{dtdx} = \frac{d\sigma_{\gamma q \rightarrow J/\psi q}}{dt} \left[\frac{81}{16} g_p(x, t) + \sum_i [q_p^i(x, t) + \bar{q}_p^i(x, t)] \right] . \quad (6)$$

Here $g_p(x, t)$, $q_p^i(x, t)$ and $\bar{q}_p^i(x, t)$ are the gluon, quark and antiquark distributions in the proton. At large t the $\gamma q \rightarrow J/\psi q$ amplitude, $f_q(s_{(c\bar{c})q}, t)$, is dominated by transition of the photon into the small $c\bar{c}$ dipole configuration which scatters elastically off the target parton and transforms into the vector meson. The dipole - gluon elastic scattering cross section is enhanced by a factor 81/16 relative to the scattering off quark. Large t ensures important simplifications. The parton ladder mediating elastic scattering of dipole is attached via two gluons to one target parton while the attachment to two and more partons in the target is strongly suppressed. Since t is the same on all rungs of the ladder, the amplitude $f_q(s_{(c\bar{c})j}, t)$ probes evolution in $\ln(1/x)$ at fixed t [13, 14]. Because the momentum transfer is shared between two gluons, the characteristic virtuality of t -channel gluons on the ladder is $\approx -t/4$ while the hard scale in the target parton density is $\approx -t$.

To the lowest order in $\ln(1/x)$, the amplitude, $f_q(s_{(c\bar{c})j}, t)$, is independent of $W_{\gamma p}$ for fixed t . Higher order terms in $\ln(1/x)$ accounted for in the leading and next-to-leading log approximations will result in increase of f_q with energy as a power of $\exp(\Delta y)$

$$f_q(s_{(c\bar{c})j}, t) \propto R(t) \left(\frac{s_{(c\bar{c})j}}{|t|} \right)^{\delta_0 + \delta' t}, \quad (7)$$

for $|t| \gg M_V^2$.

The value δ_0 changes significantly between LO and NLO BFKL, $\delta_0 \sim 0.6$ at LO and $\delta_0 \sim 0.1$ at NLO. The resummed BFKL gives a value of $\delta_0 \sim 0.2 - 0.25$ [15] over a wide range of $\alpha_s(Q^2)$. In the perturbative QCD the slope parameter δ' should be negligible ($\sim c/t$) in the $-t \rightarrow \infty$ limit. Since kinematics of HERA measurements is restricted by the interval $2\text{GeV}^2 \leq -t \leq 30\text{GeV}^2$ we keep this parameter to reveal sensitivity of the process to its value. Experimental information about $\delta(t) = \delta_0 + \delta' t$ in hard processes can be extracted, in principle, from the study of the exclusive electroproduction of light vector mesons or photo and electroproduction of heavy quarkonia. The current J/ψ data leads to $\delta_0 \sim 0.2$ for a rather wide range of Q^2 . The data on the t dependence of $\delta(t)$ in electroproduction processes at $\langle Q^2 \rangle = 8.9\text{GeV}^2$ are consistent with t independent δ , though the error bars are significantly larger in this case, for the recent results see [16, 17]. Therefore a natural guess for the value of $\delta(t)$ in the hard regime is

$$\delta(t) \approx 0.1 - 0.25 \quad (8)$$

for the t interval $2\text{GeV}^2 \leq -t \leq 30\text{GeV}^2$. In view of the theoretical uncertainties described above we will treat δ_0 and δ' as the free parameters but generally assume that $\delta(t)$ weakly depends on t .

The t -dependence of $d\sigma_{\gamma q \rightarrow J/\psi q}/dt$ originates both from the square of the energy dependent part of elastic parton - parton scattering amplitude as given by Eq. 7 and from the t -dependence of the attachments of the ladder to vector meson and parton of the target, $R^2(t)$. The large $-t \gg M_V^2$ behavior of the non-spin flip photoproduction cross section is $R^2(t) \propto 1/t^4$. The spin-flip contribution leads to $R^2(t) \propto |1/t|^3$ with strong sensitivity to the form of a vector meson-photon coupling. The HERA data on J/ψ photoproduction [8] indicate that the spin flip contribution remains a small correction in the whole studied range of t . Hence we will neglect it in the following.

The important feature of the large rapidity gap J/ψ photoproduction in a wide range of t , starting from $-t \sim \text{few GeV}^2$, is that the essential virtualities in the attachments of the ladder to the $\gamma \rightarrow J/\psi$ vertex and to the parton of the target are different. In the $\gamma \rightarrow J/\psi$ coupling all virtualities are at least of the order $m_{J/\psi}^2$. This was first observed in [18] where the process of J/ψ production was considered in the leading log BFKL approximation. Actually, this feature of the process is more general and follows from the gauge invariance. The t -dependence in the ladder -target parton block should be similar to that in deep inelastic scattering off the corresponding parton of the target - two gluons attached to this parton in the amplitude have large relative momenta and effectively act as one point-like probe of virtuality t . Experimentally scaling in DIS sets in at $Q^2 \sim 1 - 2\text{GeV}^2$. Hence, to describe the t -dependence in the J/ψ photoproduction we need in principle two scale parameters - one close to the square of the mass of J/ψ and another, t_0 , of the same order as the scale of onset of scaling in DIS.

3 Rapidity gap J/ψ photoproduction at HERA

The experimental cuts in the rapidity gap J/ψ photoproduction HERA data ([7], [8]) resulted in the relatively small rapidity interval available for gluon emission in the color singlet ladder, $\ln(xs_{\gamma p}/|t|) \leq 5$. Really, in most of the probed settings the invariant energy of the dipole-parton system was rather low, $W_{\bar{q}q-j} \leq 20\text{GeV}$. Since only single gluon emission is allowed for such energies in the ladder kinematics, it is hardly justified to apply a BFKL-type approximation. Hence, we need some reasonable QCD motivated

parametrization of the cross section based on Eq.6. It should account for the discussed above two scales characterizing onset of hard processes in the large rapidity gap J/ψ photoproduction and should be applicable in a wide region of t , not only to asymptotically large t . We find that the simplest choice is :

$$\frac{d\sigma_{\gamma+p \rightarrow J/\psi+Gap+X}}{dt} = \frac{CI(x_{\min}, t)}{(t_0 - t)(M_{J/\psi}^2 - t)^3} \cdot \left[\frac{W_{\gamma p}^2}{\sqrt{(t_0 - t)(M_{J/\psi}^2 - t)}} \right]^{2\delta(t)}. \quad (9)$$

The factor $I(x_{\min}, t)$, is obtained by integrating the parton densities over x ,

$$I(x_{\min}, t) = \int_{x_{\min}}^1 dx x^{2\delta(t)} \left[\frac{81}{16} g_p(x, t) + \sum_i [q_p^i(x, t) + \bar{q}_p^i(x, t)] \right]. \quad (10)$$

To calculate $I(x_{\min}, t)$ we used the CTEQ6M PDFs [19]. The value of x_{\min} was calculated using Eq.(4) separately for each of experimental sets of the ZEUS and H1 data using reported cuts on M_X . The values of δ_0, δ' in $\delta(t) = \delta_0 + \delta' t$ and constant C were adjusted to provide a reasonable description of the J/ψ photoproduction at HERA.

There are exists two sets of the large t and rapidity gap J/ψ data . Collaboration ZEUS [7] measured the t -dependence of cross section in the range $1 \text{ GeV}^2 < -t < 8 \text{ GeV}^2$ at the average energy $\langle W_{\gamma p} \rangle \approx 100 \text{ GeV}$ using the following cuts: $x_{\min} = \frac{-t}{W_0^2}$ with $W_0 = 25 \text{ GeV}$ if $x_{\min} > 0.01$ otherwise $x_{\min} = 0.01$. In the experiment of H1 collaboration [8] the t -dependence has been measured in the wider interval $2 \text{ GeV}^2 < -t < 30 \text{ GeV}^2$ averaging the cross section over the energy in the range $50 \text{ GeV} \leq W_{\gamma p} \leq 150 \text{ GeV}$ and assigning the averaged cross section to the value $W_{\gamma p} \approx 100 \text{ GeV}$. The restriction on the mass of the produced system M_X , $M_X^2 \leq 0.05 W_{\gamma p}^2 + t$, applied in H1 experiment leads to the energy dependent value of x_{\min} . This means that the cross section has to be integrated over x in the interval $x_{\min} < x < 1$. before averaging over energy at each value of t .

We find that these data are consistent (fig.1) with t dependence predicted by QCD dominance of one gluon exchange in the charmonium wave function ($d\sigma/dt \propto t^{-4}$) and the shape of the curve is not sensitive to the parameter δ_0 which characterizes explicit energy dependence of the amplitude of dipole scattering off a constituent of the target. The t dependence of cross section is described reasonably well with the values: $C = 0.9$ if $\delta_0 = 0.$, $C = 0.4$ if the parameter $\delta_0 = 0.1$ and $C = 0.2$ for $\delta_0 = 0.2$ at not too large values of

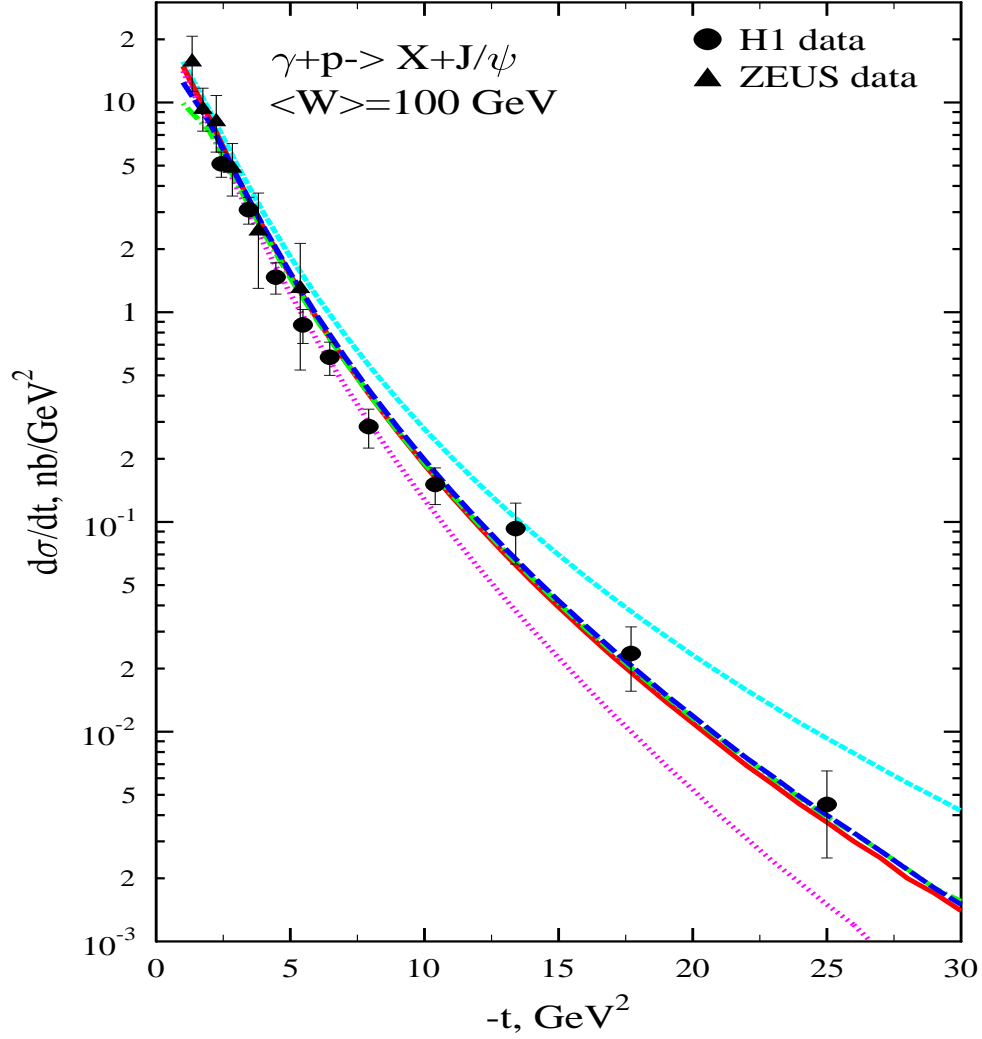


Figure 1: Momentum transfer distribution for J/ψ photoproduction in H1 and ZEUS. Solid-long-dashed curve corresponds to the choice of $\delta_0 = 0, 0.1, 0.2$ with $\delta' = 0.01$. Short-dashed curve - $\delta' = 0.0$ and dotted curve $\delta' = 0.02$. Here we determine the parameter δ' and the normalization constant C for each value of δ_0 .

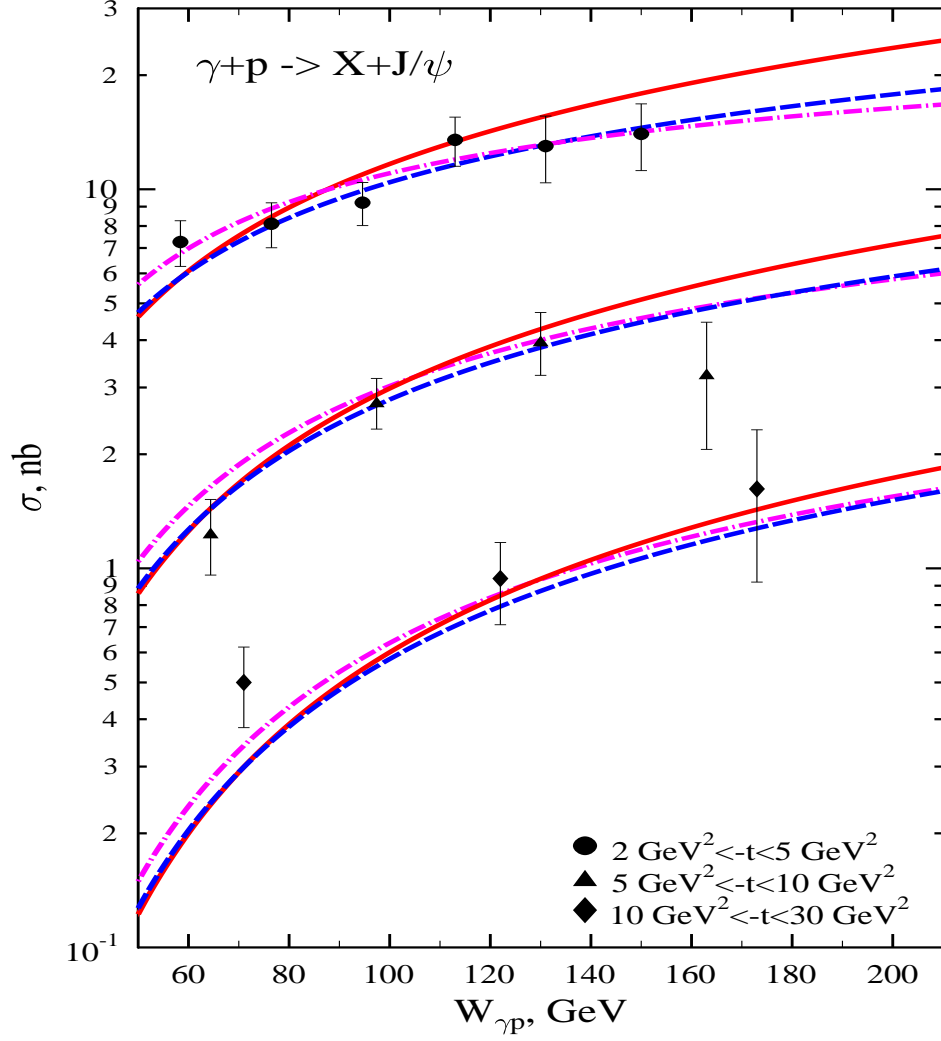


Figure 2: Energy dependence (choice of δ_0) for J/ψ photoproduction in experiment of H1 at HERA. No free parameters used in calculations. Solid line corresponds to $\delta_0 = 0.2$, dashed line - $\delta_0 = 0.1$ and dot-dashed line $\delta_0 = 0$.

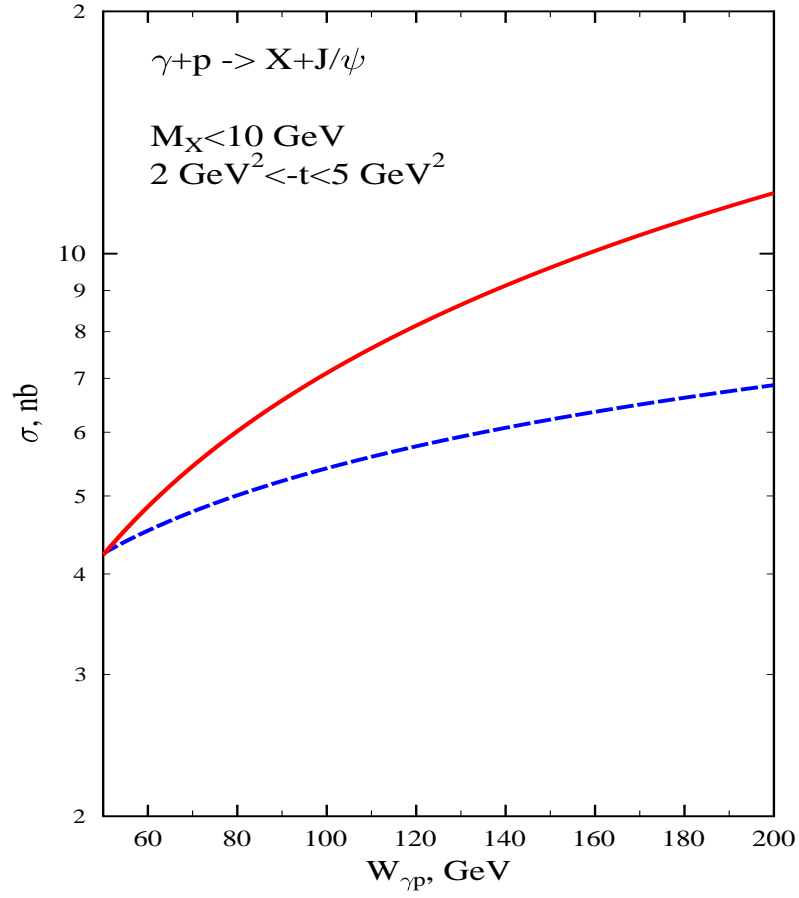


Figure 3: Energy dependence for J/ψ photoproduction at HERA in kinematics of fixed upper limit of the diffractively produced mass $M_{max} = 10 \text{ GeV}$. Solid line corresponds to $\delta_0 = 0.2$ and dashed $\delta_0 = 0.1$. These calculations demonstrate that measurements of cross section in such kinematics could allow one to determine reliably the parameter δ_0 .

t . Since the parameter δ_0 is appeared to be comparatively small it is evident that there is definite sensitivity to the slope parameter δ' at large t . From comparison with the data the value $\delta' = 0.01 \text{ GeV}^2$ seems to be reasonable.

The H1 collaboration also presented the data for the energy dependence of cross section for three intervals of t . In this kinematics dependence of cross section on $W_{\gamma p}$ is determined by the factor $W_{\gamma p}^{4\delta(t)}$ in the cross section of dipole-parton interaction and by integral over x of weighed by factor $x^{2\delta(t)}$ the parton distributions within the proton. With an increase of the energy the value of x_{min} is decreasing and due to the strong growth of the gluon distributions in the proton the integral over x rapidly grows. From comparison of the results of calculations with the data we found that in the kinematics covered by HERA, i. e. with the energy dependent cut on the mass M_X of the produced system, increase of cross section with energy is due to the growth of $I(x_{min}, t)$ related to the increase of the gluon distributions rather than due to the factor $W^{4\delta(t)}$. So, we conclude that the kinematical cut imposed in the H1 experiment results in a weak sensitivity of the data to actual value of $\delta(t)$, see Fig.2.

One can achieve a better sensitivity to δ_0 if the cross section were studied as a function of energy at fixed M_X (fixed x) or for $M_X \leq const$. In the latter case the integral of parton distribution over x is constant and the energy dependence follows from the amplitude of dipole-parton interaction. For the illustration we present in Fig.3 results of the calculations for such M_X cut in the kinematics of H1.

Thus our analysis shows that H1 and ZEUS data on large t large rapidity gap processes are consistent with the t -dependence expected in pQCD which is a combination of t -dependence due to the structure of the $q\bar{q}$ vector meson wave function and the t -dependence of the amplitude of dipole-parton scattering. At the same time data are insensitive to the energy dependence of the amplitude of dipole-parton scattering which can not be reduced to parton distributions in a hadron. To probe pQCD predictions for this amplitude one need to perform measurements in different kinematics and at significantly larger collision energies which can be achieved in ultraperipheral collisions at LHC.

4 Rapidity gap J/ψ photoproduction in ultraperipheral pA collisions at the LHC.

It is unlikely that further HERA studies will cover a sufficiently wide range of $W_{\gamma p}$ and Δy to study the energy dependence of the large- t elastic dipole-parton scattering amplitude. On the other hand, at the LHC, CMS and ATLAS will have sufficient rapidity coverage to study the process in Eq. (2) in ultraperipheral pA collisions. To estimate the large t rapidity gap J/ψ photoproduction cross section in ultraperipheral pA collisions at the LHC we use the parametrization of the $\gamma p \rightarrow X J/\psi$ cross section in Eqs. (9). We do not address the pA contribution from $\gamma A \rightarrow J/\psi X$ since it is much smaller and can easily be separated experimentally. The large t nucleon-dissociation cross section is then

$$\frac{d\sigma_{pA \rightarrow J/\psi X A}}{dtdy} = \frac{dN_\gamma^Z(y)}{dk} \frac{d\sigma_{\gamma N \rightarrow J/\psi + rap\ gap + X}(y)}{dt}, \quad (11)$$

where $dN_\gamma^Z(y)/dk$ is the photon flux generated by the ion with energy $k = (M_{J/\psi}/2) \exp(y)$. We consider intermediate and large momentum transfer in UPCs at the LHC, analogous to those studied at HERA.

To check feasibility of such measurements and their sensitivity to the value of δ we performed calculations of the cross sections of rapidity gap events with J/ψ in ultraperipheral proton-ion collisions at LHC for the interval of the J/ψ rapidities $-4 \leq y \leq 4$ which corresponds to the range of energies $W_{\gamma p}$ from about 40 GeV up to 1 TeV. Results are also shown for two assumptions of δ_0 : 0.2 and 0.1. We do not consider $W_{\gamma p} < 20$ GeV where our HERA-based parametrization, Eqs. (9) and (10), is unreliable.

We study the cross section when $M_X \propto W_{\gamma p}$, specifically $M_X^2 \leq 0.05 W_{\gamma p}^2 + t$ at fixed t , Fig.4(left). This cut corresponds to fixing Δy and changing x_{\min} . Such studies could test the parton distribution functions and the reaction mechanism by extracting $I(x_{\min}, t)$ from the data in different x_{\min} and t bins.

The cross section can also be studied at fixed t as a function of the vector meson rapidity with the restriction $M_X \leq const$ to determine the energy dependence of the dipole-parton amplitude and thus $\delta(t)$. In this case, x_{\min} does not depend on $W_{\gamma p}$ and the dipole-parton elastic scattering amplitude varies with $W_{\gamma p}$ due to the increase of the rapidity gap with y . Most events in

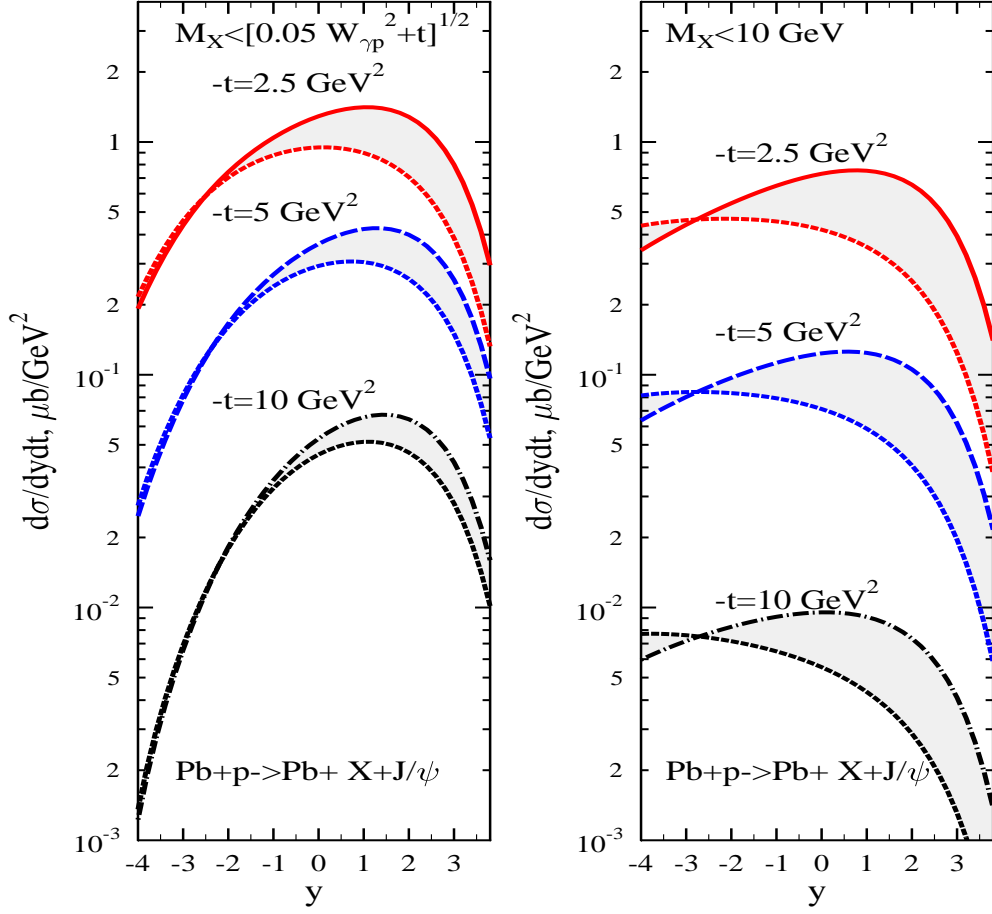


Figure 4: Rapidity distributions for the J/ψ photoproduction in the ultraperipheral proton-Pb collisions at LHC in kinematics with the gap between J/ψ and diffractively produced system with the mass in the range $m_N < M_X \leq \sqrt{0.05W_{\gamma p}^2 + t}$ (left) and in the range $m_N < M_X \leq 10 \text{ GeV}$ (right) at different values of the momentum transfer. The solid, long dashed and dot-dashed lines present cross sections calculated with $\delta_0 = 0.2$ and the short dash lines with $\delta_0 = 0.1$.

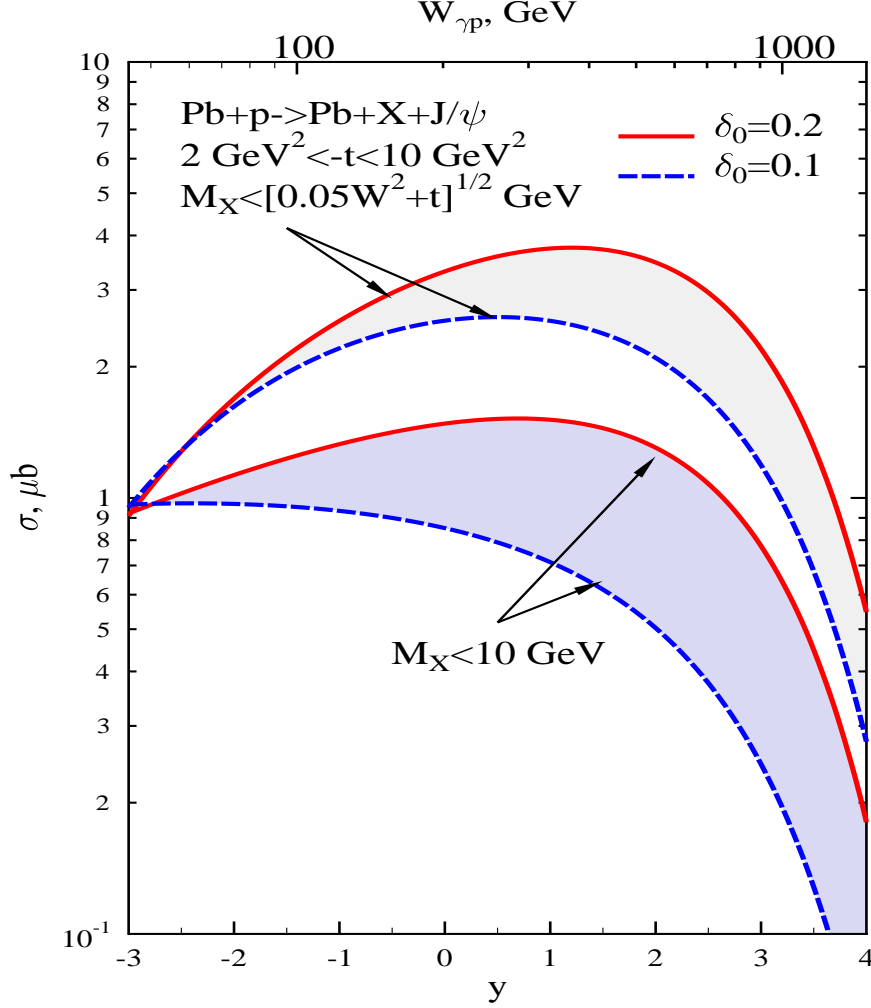


Figure 5: Rapidity distributions for the J/ψ photoproduction in the ultraperipheral proton-Pb collisions at LHC in kinematics with the gap between J/ψ and diffractively produced system with the mass in the ranges $m_N < M_X < \sqrt{0.05W_{\gamma p}^2 + t}$ and $m_N < M_X < 10 \text{ GeV}$. The cross sections are integrated over t in the range $2 \text{ GeV}^2 \leq -t \leq 10 \text{ GeV}^2$.

Cut on M_X	$M_X \leq 10 \text{ GeV}$	$M_X \leq \sqrt{0.05 W_{\gamma p}^2 + t}$
p - Ar	$0.6 \mu b$	$1.2 \mu b$
p - Pb	$9 \mu b$	$18 \mu b$

Table 1: Total cross sections of the large rapidity gap J/ψ photoproduction in ultraperipheral p-Ar and p-Pb collisions.

the kinematics with $M_X \leq 10 \text{ GeV}$ and $2 \text{ GeV}^2 \leq -t \leq 10 \text{ GeV}^2$ correspond to $x \geq 0.01$ where the scattering of dipole off the gluons of the target give the dominant contribution. Because of the specifics of the LHC detectors it will be probably very difficult to reach the x range where quark scattering is larger than gluon scattering, $x \geq 0.4$. Thus we can primarily infer the energy dependence of the elastic ($c\bar{c}$)-gluon amplitude at different t . Overall, the energy range, $s_{\text{max}}/s_{\text{min}} \geq 10^3$, is large enough for precision measurements of the energy dependence of the amplitude. If $\delta(t) \approx 0.2$, the elastic cross section should increase by a factor of ~ 30 in the energy range.

The two choices of M_X cut exhibit the same behavior at large forward rapidity due to the steep decrease of the photon flux.

The cross section integrated over t in the range $2 \text{ GeV}^2 \leq -t \leq 10 \text{ GeV}^2$ are presented in Figs.5. The total cross sections integrated over the interval of rapidities $-4 \leq y \leq 4$ for two considered cuts on the mass of produced system M_X are given in Table 1. The rates, which can be obtained multiplying the cross sections by luminosities of 6 and $0.4 \mu b^{-1}$ for $p\text{Ar}$ and $p\text{Pb}$ respectively, are high (even when one takes into account a small decay branching ratio of J/ψ into leptons which is not included in the table)

One can see that cross sections are large in the rapidity range where the LHC detectors have good acceptance to J/ψ 's with transverse momenta of few GeV and that with the cuts natural for LHC there is a strong sensitivity to the value of the δ parameter.

Hence we conclude that measurements of the discussed processes in pA collisions at LHC would allow to measure energy and momentum transfer dependence of the hard vacuum exchange.

5 Conclusions

Studies of rapidity gap processes in the proton-ion UPCs at the LHC will directly measure the energy dependence of the large- t elastic amplitude of dipole-parton scattering in the wide range of energies. We find that it will be possible to study the J/ψ photoproduction in such processes up to $W_{\gamma p} \sim 1$ TeV, extending the energy range studied at HERA by a factor of 10. This should allow us to investigate hard QCD dynamics up to $xs_{\gamma p}/|t| \sim 10^5$ that corresponds to rapidity interval of ~ 8 units for gluon emission. The rapidity interval between two gluons on the ladder is ≥ 2 , hence, the emission of several gluons is possible in the ladder in such processes thus making applicability of the BFKL approach more justified. These measurements will be also important as a reference for the study of a similar process in the nucleus-nucleus collisions at the LHC which will be considered in a separate publication (for discussion of the analogous process of large t ρ -meson production in the nucleus-nucleus collisions see [12]).

Acknowledgments

This work was supported in part by the US Department of Energy, Contract Number DE-FG02-93ER40771 (M. Strikman, M. Zhalov); L.Frankfurt and MS thank BSF for support; M. Zhalov would like to express acknowledgment for support by CERN-INTAS grant no 05-103-7484 .

References

- [1] I. P. Ivanov, N. N. Nikolaev and A. A. Savin, Phys. Part. Nucl. **37** (2006) 1 [arXiv:hep-ph/0501034].
- [2] H. Abramowicz, L. Frankfurt and M. Strikman, *Proc. SLAC Summer Inst.* p 539, 1994; Surv. High Energy Phys. **11** (1997) 51.
- [3] J. R. Forshaw and M. G. Ryskin, Z. Phys. C **68** (1995) 137 [arXiv:hep-ph/9501376].
- [4] J. Bartels, J. R. Forshaw, H. Lotter and M. Wusthoff, Phys. Lett. B **375** (1996) 301 [arXiv:hep-ph/9601201].

- [5] M. Derrick *et al.* [ZEUS Collaboration] Phys. Lett. B **369** (1996) 55 [arXiv:hep-ex/9510012].
- [6] C. Adloff *et al.* [H1 Collaboration] Eur. Phys. J. C **24** (2002) 517 [arXiv:hep-ex/0203011].
- [7] S. Chekanov *et al.* [ZEUS Collaboration] Eur. Phys. J. C **26** (2003) 389 [arXiv:hep-ex/0205081].
- [8] A. Aktas *et al.* [H1 Collaboration] Phys. Lett. B **568** (2003) 205 [arXiv:hep-ex/0306013].
- [9] A. Aktas *et al.* [H1 Collaboration] Phys. Lett. B **638** (2006) 422 [arXiv:hep-ex/0603038].
- [10] L. Frankfurt, M. Strikman and M. Zhalov, Phys. Lett. B **640** 162 (2006) [arXiv:hep-ph/0605160].
- [11] L. Frankfurt, M. Strikman and M. Zhalov, arXiv:hep-ph/0612072.
- [12] A. J. Baltz *et al.*, Phys. Rept. **458** (2008) 1 [arXiv:0706.3356 [nucl-ex]].
- [13] L. Frankfurt and M. Strikman, Phys. Rev. Lett. **63** (1989) 1914 [Erratum-ibid. **64** (1990) 815].
- [14] A. H. Mueller and W. K. Tang, A. H. Mueller and W. K. Tang, Phys. Lett. B **284** (1992) 123.
- [15] G. P. Salam, arXiv:hep-ph/0501097.
- [16] A. Levy *Nucl. Phys. Proc. Suppl.* **146** (2005) 92. [arXiv:hep-ex/0501008].
- [17] A. Aktas *et al.* [H1 Collaboration], Eur. Phys. J. C **46** (2006) 585 [arXiv:hep-ex/0510016].
- [18] R. Enberg, J. R. Forshaw, L. Motyka and G. Poludniowski, JHEP **0309** (2003) 008 [arXiv:hep-ph/0306232].
G. G. Poludniowski, R. Enberg, J. R. Forshaw and L. Motyka, JHEP **0312** (2003) 002 [arXiv:hep-ph/0311017].
- [19] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky and W. K. Tung, JHEP **0207** (2002) 012 [arXiv:hep-ph/0201195].